Study of plasma waves induced through the wake formation process behind an ionospheric sounding rocket

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論　文　内　容　要　旨

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学位論文の 題　　　目	Study of plasma waves induced through the wake formation process behind an ionospheric sounding rocket （電離圏観測ロケットのウェイク形成過程に伴い励起するプラズマ波動の研究）		

Contents

Abstract

A sounding rocket is a powerful tool of in-situ measurement in the lower ionosphere. It enables us to simultaneously obtain data about plasmas such as number density, temperature, drift velocity, and electromagnetic field with high space resolution. However, a sounding rocket moving supersonically in the ionosphere interacts with the surrounding plasma, which leads to the formation of a rarefied plasma region called ‘plasma wake’ behind the rocket. Through a few rocket experiments carried out previously, it has been suggested that plasma waves are excited around the rocket wake as reported by Yamamoto (2001). Based on cold plasma theory, Yamamoto (2001) concluded that the observed waves were upper hybrid resonance (UHR) mode waves because the wave frequencies correspond to those of UHR mode waves under the wake conditions. Yamamoto (2001) also suggested that the generation mechanism could be a two-stream instability driven by incident electrons from both sides of the wake edges. However, there remains the issue that a part of the observed wave frequencies were not satisfied with the UHR mode dispersion relation and that the proposed mechanism has not been verified experimentally. In order to investigate the process of plasma expansion into a void, Singh et al. (1987) carried out a one-dimensional Vlasov-Poisson simulation and showed that two- or multi-stream electrons appear on the wake-axis up to 1.3 % of the near-wake region (ion void or the most diluted region nearest spacecraft). However, the electron distribution function in other part of the plasma wake could not be reported due to the effect from the boundaries [Singh et al., 1987], lack of computational resources, and large numerical errors from particle-in-cell (PIC) like calculation scheme in time development of the electron distribution function [Sakanaka

et al., 1971; Singh, 1980].

In this study, we re-discuss wake-induced plasma waves around an ionospheric sounding rocket by using data from the S-520-26 rocket experiment, reported by Endo et al. (2015), and from one-dimensional Vlasov-Poisson simulations.

First, we analyze the data from S-520-26 NEI/PWM (Impedance probe / Plasma Wave Monitor) [Suzuki, PhD thesis, 2011], which is a combined system that consists of an impedance probe and a plasma wave receiver. Its time resolution is about 260 ms, improved from that used in previous rocket experiments [Yamamoto, 2001; Uemoto, 2008]. This system enables us to investigate the wake structure and the spin-phase dependence of wave intensities in more detail. The result shows that electron density profiles below an altitude of 298 km are obtained inside and outside the wake and that three kinds of plasma waves (Group A, B, and C waves) are also observed. The frequency characteristics of Group A waves is similar to the UHR mode waves reported in previous studies [Yamamoto, 2001; Uemoto, 2008]. Using electron density data and considering that Group A waves could be generated in the near-wake, we conclude that the Group A waves are short-wavelength electrostatic waves including electrostatic electron cyclotron harmonic (ESCH, ECH) and UHR mode waves based on hot plasma theory. Group B and Group C waves are identified as whistler mode waves. Improved time resolution of NEI/PWM enables us to find the spin-phase dependence of the observed plasma waves. Considering that the observed waves could be generated in the near-wake, and therefore they could be short-wavelength electrostatic modes, we conclude that the obtained spin-phase dependence should represent the spatial distribution of free-energy sources for plasma wave instabilities. The actual distribution functions around the rocket wake, however, are not well known, and the relation with the wake formation process is unclear.

Therefore, in the present study, we develop a one-dimensional Vlasov-Poisson code and carry out simulations on our own. We assume a simulation model similar to that adopted by Singh et al. (1987), in which plasma expands into a void region along the magnetic field line. In this simulation, the time variation of plasma distribution was regarded as the spatial variation downstream. In order to solve the Vlasov equation numerically, we adopted the time-splitting method [Cheng and Knorr, 1976] and the rational CIP method [Nakamura and Yabe, 1999] as used in Abe (2006). We perform simulations for two cases of ion-electron mass ratio: $m_i/m_e = 2.9\times10^4$ assuming O^+ dominated plasmas in the lower ionosphere and $m_i/m_e = 40$. In the latter case, we achieve calculation up to 43% of near-wake region, and find six types of charge density disturbances including Langmuir waves propagating from the wake edge to the outside and inside of the wake. The obtained Langmuir waves are triggered by an oscillating electric field around the wake edge. The oscillating electric field generates electron beams associated with the Langmuir waves. The electron beams form non-Maxwellian distribution functions around the wake edge. At the wake center, we obtain two- or multi-stream electrons, which are produced mainly by the negative wake potential. These simulation results indicate that non-Maxwellian electrons are created due to both the inward polarization electric field formed close to the wake axis, and the oscillating electric field appearing more outside.

In this study, we propose a model of the generation of wake-induced plasma waves behind an ionopheric sounding rocket based on observational results. That is, the induced waves are short-wavelength electrostatic waves, and they are excited by non-Maxwellian electron distributions. The present simulation results show that the wake-filling process along the magnetic field can produce anisotropic electrons around the rocket wake. The proposed model should be confirmed more quantitatively and realistically by considering multi-dimensional effects including the Lorentz force from a magnetic field.

別　紙

論文審査の結果の要旨

観測ロケットは下部電離圏のその場観測を行う有力な手段で，プラズマの数密度，温度，ドリフト速度，背景の電磁場の高分解能のデータを同時に得ることができる．一方で，電離圏を飛翔するロケットは，自然の状態のプラズマに影響を与えることも明らかとなっており，ロケット後方に「プラズマウェイク」と呼ばれる領域を形成する．従来行われてきたロケット実験では，ウェイク付近でのプラズマ波動の励起が示唆されており［Yamamoto, 2001; Uemoto, 2008］，山本(2001)は，コールドプラズマ近似をもとに，これらのプラズマ波動がウェイクの両側から侵入した電子に起因する二流体不安定によって生じた高域混成共鳴波(UHR)であると結論した．また，Singh et al. (1987)は，１次元ブラソフシミュレーションを実施して，ウェイク中央付近に２成分ないし多成分の電子ビームが生じることを示した．

遠藤研提出の博士論文は第一に，観測ロケット S-520-26 で観測されたウェイク励起プラズマ波動の解析を行った．従来の観測ロケットよりも高時間分解能（250ms 間隔，スピン毎に 4 サンプル）の電子数密度，プラズマ波動データの解析から，高度 298km までのウェイク内外での電子数密度の鉛直分布，ウェイク周辺での３タイプのプラズマ波動の励起が明らかにされた．そのうちの１タイプは，従来の研究で報告されてきたプラズマ波動に対応している．本研究の解析からこの波動は，ウェイク内を発生領域とし，ホットプラズマによって励起された静電的電子サイクロトロン波(ESCH)および UHR 波と結論された．一方，残りの２タイプの波動は，ホイッスラモードと推定された．本研究の解析から，ウェイク側面付近に発生領域をもつことが示唆された．以上の成果は Endo et al. (2015)として学術誌に報告済みである．

本博士論文では第二に，Time-splitting 法［Cheng and Knorr, 1976］および有理関数 CIP 法［Nakamura and Yabe, 1999; Xiao et al., 1999］を採用した高精度の１次元ブラソフシミュレーションコードを開発し，数値シミュレーション研究を実施した．ウェイク中での速度分布関数の時間発展を議論した Singh et al. (1987)の計算では，ウェイク中の特にロケット近傍のイオンウェイク領域の 1%にとどまっていた再現範囲を，42%まで拡大することに成功した．イオン・電子質量比が現実と同程度の場合（2.9×10^4），現実より小さい場合（40）でそれぞれ計算を行い，イオンウェイクの壁から内外に伝搬する擾乱など，6 タイプの電荷擾乱の発生を確認した．シミュレーション結果の解析から，擾乱の起源はウェイク境界において発生する振動電場ならびにウェイク中での負のポテンシャルによること，振動電場により発生し伝搬する擾乱の波数および周波数が Langmuir 波の分散関係を満たすこと，負のウェイクポテンシャルがウェイク中央付近での 2 成分ないし多成分の電子ビームを生成している要因となっていることをそれぞれ明らかとした．

以上の観測データの解析ならびにシミュレーションの結果から，観測ロケットの後方に形成されるウェイクの中央および境界付近において，非等方的な速度分布の電子が生成され得ることが示された．これらはウェイク中の負ポテンシャルと，ウェイク境界付近の電場振動によって生じ，S-520-26 ロケット実験で観測されたようなプラズマ波動の生成に寄与するものであったことが示唆された．本論文の主たる成果は，これまでに国内外の学会・研究会で公表されるとともに，本人主著の学術論文として１編を出版済みである．

これらは論文提出者が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している．したがって，遠藤研提出の博士論文は、博士（理学）の学位論文として合格と認める．